RELIABILITY-BASED CONTROL ALGORITHMS FOR NONLINEAR HYSTERETIC SYSTEMS

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Introduction

Structural reliability is commonly defined as the probability of demand not exceeding a predefined limit that represents the capacity of the structure. The limit state functions are often established using engineering demand parameters such as maximum inter-story drift, maximum absolute acceleration, and maximum shear force. Using these functions, reliability analysis enables probabilistic assessment of the ability of a system to meet a set of performance criteria, while accounting for various uncertainties that may affect system's performance. **Reliabilit**y concepts can therefore be employed in control design to effectively enhance the performance of systems under external disturbances such as natural hazards. However in conventional feedback controllers, reliability as a performance metric is not explicitly considered. In this research, reliability is incorporated in **Hazard Mitigation and Control (HMC)**. The family of nonlinear controllers using stochastic averaging of energy envelope is extended to properly integrate reliability metrics in the design of **stochastic controllers**.

Aim

The goal is to develop a reliability based stochastic control system than can

- Reduce maximum inter-story drifts in buildings
- Suppress the absolute acceleration of floors
- Enhance the reliability of structures
- Adapt to sudden events and uncertainties in systems
- Minimize retrofit and repair costs of structures over their service life
- **Reduce the likelihood of failure**

Table 1. MCS results of reliability-based measures at an intensity level of 0.32 g.

γ_{BW} = 5.82 m^{-1}				
Reliability Measures	URC	CRC	SLQR	Uncontrolled
$P(e \geq e_c)$	0.074	0.097	0.126	0.864
$P(DR \geq 0.20\%)$	0.087	0.116	0.192	0.600
γ_{BW} = 29.1 m^{-1}				
Reliability Measures	URC	CRC	SLQR	Uncontrolled
$P(e \geq e_c)$	0.048	0.058	0.078	0.608
$P(DR \geq 0.20\%)$	0.035	0.054	0.123	0.416

Methods

Two control algorithms are proposed including **constrained** and **unconstrained reliability-based control strategies**. In the constrained approach, first- and second-level optimizations are implemented. The first-level optimization entails obtaining the value function of the **Hamilton-Jacobi-Bellman (HJB)** equation (Fleming and Soner, 2006) through enhanced stochastic averaging of energy envelope. The second-level optimization considers minimizing **the probability of failure** subjected to force constraints by searching for gain parameters in the objective function. Here, the probability of failure is defined as the likelihood of exceeding a predefined limit. In the unconstrained approach, a single optimization process is utilized to minimize the probability of failure by directly searching for the optimal control gain.

After modelling the uncontrolled system, the Itô equation of the controlled system is derived by adding the effect of the control force.

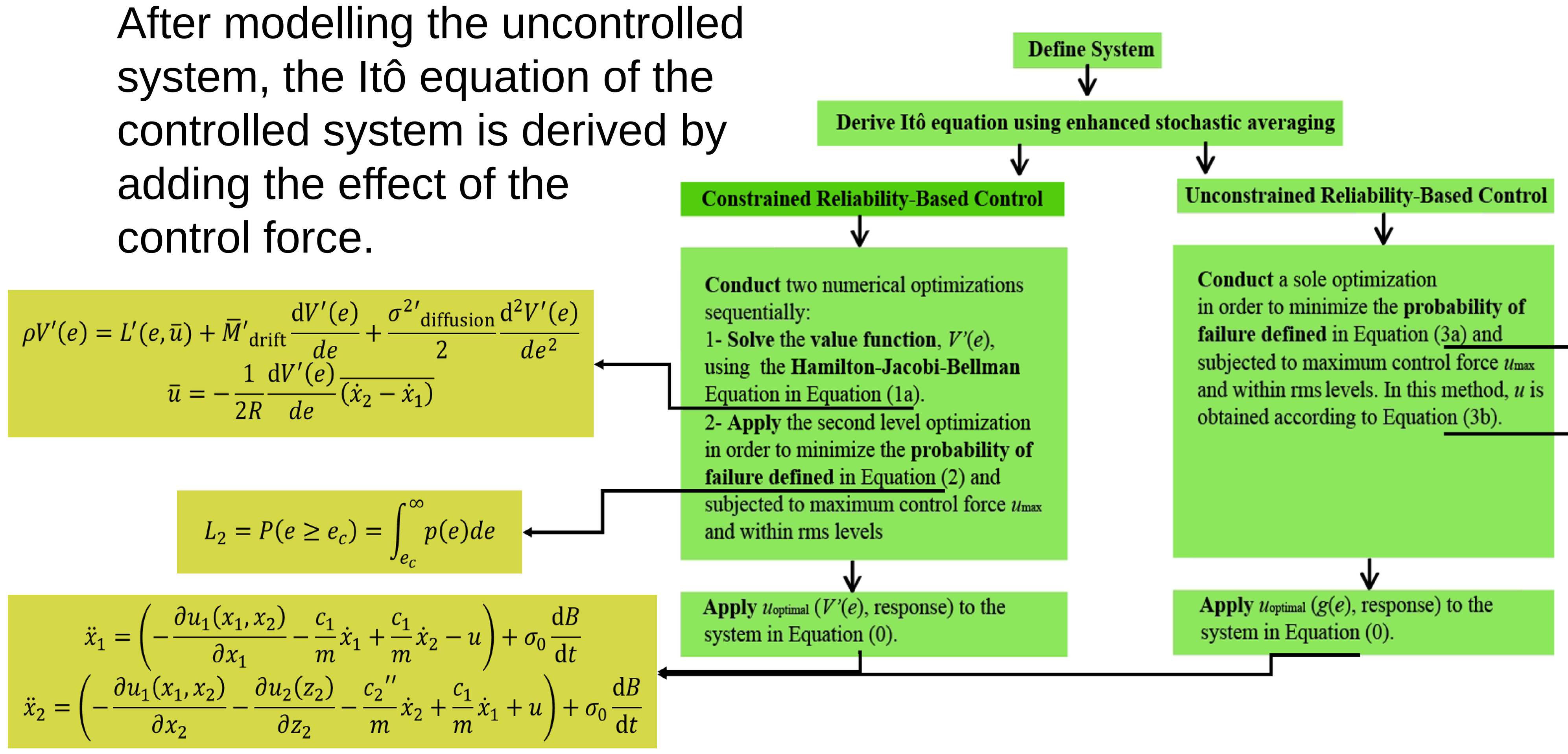

Figure 1. Flow chart of Reliability-Based Control Algorithms.

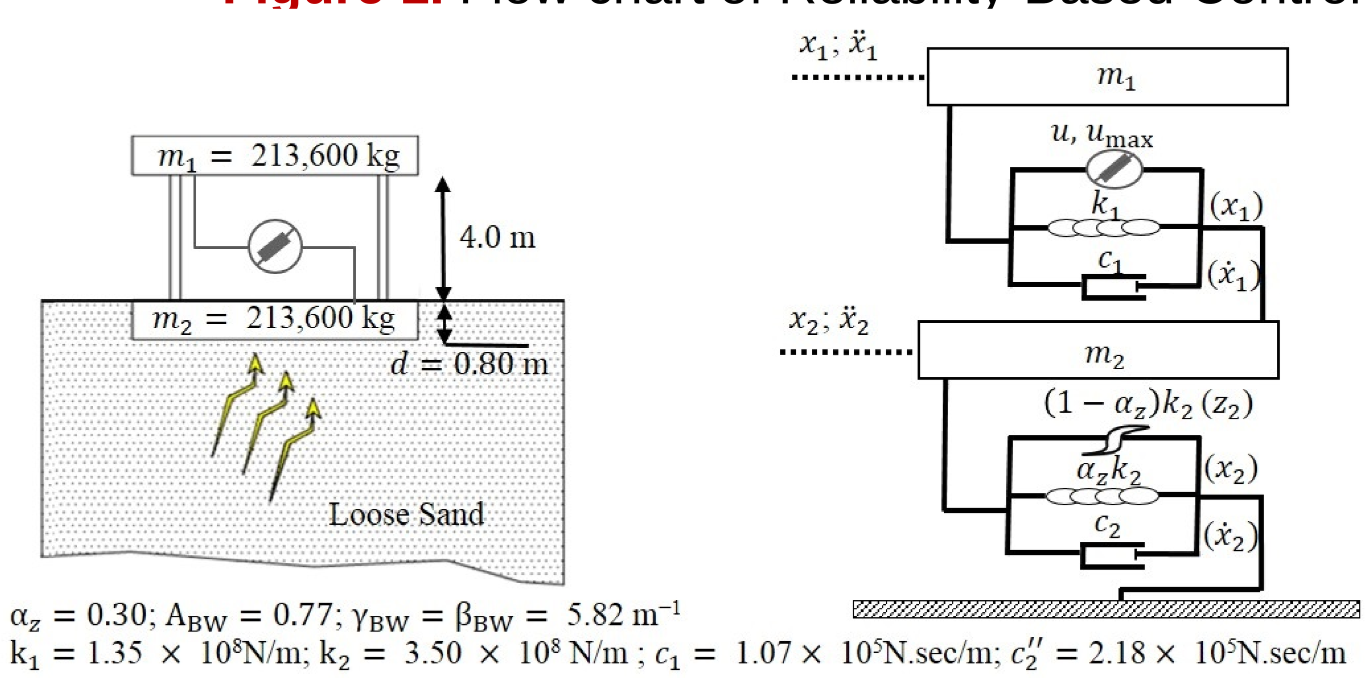

Figure 2. Building model (a) schematic of the soil-foundation-structure system, (b) the representative lumped model.

Kobe	Peak/RMS		
State	$(x_2 - x_1)$ (mm)	x_2 (mm)	$\ddot{x}_{1A}$ (m/sec^2)
Uncontrolled	27.9/5.5	29.9/5.0	17.60/3.50
URC	15.2/3.0	23.0/3.4	12.72/2.18
CRC	16.7/3.2	23.3/3.4	12.81/2.12
SLQR	20.0/3.5	29.6/3.6	13.71/2.35

Table 2. Simulation results for control cases for the modified system (γ_{BW} = 29.1 m^{-1}): relative displacement $(x_2 - x_1)$, foundation displacement x_2, and roof absolute acceleration, $\ddot{x}_{1A}$.

Results

The performance of the proposed methods is demonstrated for seismic response control of a structure on a nonlinear shallow foundation in loose sand. The constrained reliability-based control (CRC) and unconstrained reliability-based control (URC) algorithms are designed, optimized, and applied, and their performance

$$L_0 = P(e \geq e_c) = \int_{e_c}^{\infty} p(e)de$$
$$\bar{u} = -\frac{1}{2R}g(e)\overline{(\dot{x}_2 - \dot{x}_1)}$$

is compared to stochastic LQR (SLQR) and uncontrolled cases. The controlled and uncontrolled systems are subjected to white noise excitations with various intensity levels (σ_0 = 0.12 g, 0.20 g, 0.32 g) as well as ground motions from historic earthquakes including 1994 Northridge (peak ground acceleration (PGA) = 1.33 g recorded at the Sepulveda Veterans Hospital station), 1940 El-Centro (PGA = 0.35 g recorded at the Imperial Valley Irrigation District station), and 1995 Kobe (PGA = 1.28 g recorded at the Kobe University station). The ground motions were extracted from the PEER Strong Motion Database.

Conclusion

The failure probability based on drift P(DR ≥ 0.20%) for URC, CRC, SLQR, and uncontrolled cases are 8.7%, 11.6%, 19.2%, and 60.0%, respectively. In terms of response reduction, the reduction of the system response under Kobe ground motion reached around 25% with respect to SLQR at equivalent control forces. Those methodologies can be extended to risk-based and resilient-based control methods.

Bibliography

El-Khoury, O. and Shafieezadeh, A. (2016), "Reliability-Based Control Algorithms Using Enhanced Stochastic Averaging In Active Control Of Seismic-Excited Hysteretic Systems." Earthquake Engineering and Structural Dynamics, In Submission.